

# A Joint Model for IEEE 802.15.4 Physical and Medium Access Control Layers

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**Abstract**—Many studies have tried to evaluate wireless networks and especially the IEEE 802.15.4 standard. Hence, several papers have aimed to describe the functionalities of the physical (PHY) and medium access control (MAC) layers. They have highlighted some characteristics with experimental results and/or have attempted to reproduce them using theoretical models. In this paper, we use the first way to better understand IEEE 802.15.4 standard. Indeed, we provide a comprehensive model, able more faithfully to mimic the functionalities of this standard at the PHY and MAC layers. We propose a combination of two relevant models for the two layers. The PHY layer behavior is reproduced by a mathematical framework, which is based on radio and channel models, in order to quantify link reliability. On the other hand, the MAC layer is mimed by an enhanced Markov chain. The results show the pertinence of our approach compared to the model based on a Markov chain for IEEE 802.15.4 MAC layer. This contribution allows us fully and more precisely to estimate the network performance with different network sizes, as well as different metrics such as node reliability and delay. Our contribution enables us to catch possible failures at both layers.

**Index Terms**—IEEE 802.15.4; Physical layer modeling; Medium Access Control

## I. INTRODUCTION

Wireless sensor networks have been closely studied in recent years. Several studies have investigated behaviors and performances of these networks. Some of them have highlighted such networks properties by relying on empiric results [2]–[6] whereas others have focused on reproducing a standard or mechanism functionalities tied to sensors by proposing analytical models [1], [7]–[9]. Empirical studies have shown that wireless communication networks are radically different from some simulation models (disc-shaped nodes range for example). Analytical studies have attempted to reproduce mechanisms and technical aspects widely used/seen in these networks in order to track network performances. Among these approaches, those of Zuniga and Krishnamachari [10], [11] stand out. They emphasize the limits of disc-shaped node range models that are used in simulators, and highlight the existence of a transitional region between the connected and disconnected areas. This observation, based on experiments, enables us to understand clearly the reason behind link unreliability in low power wireless networks. Moreover, Zuniga and Krishnamachari underline the impact of asymmetry in transitional region expansion and its negative effect on reliability [11]. Meanwhile, lot of the performance analysis

of MAC layer protocol are derived from the Markov model proposed by Bianchi [7] for the IEEE 802.11 standard [12]. This model consists in a Markov chain that reproduces the functionalities of the IEEE 802.11 standard while assuming saturated traffic and ideal channel conditions. This approach has inspired many others, for instance the Park et al. model [1]. It presents itself as a relevant contribution which aims to measure reliability, delay and energy consumption in a wireless network based on IEEE 802.15.4 standard [13]. In this paper, we develop an IEEE 802.15.4 model that takes into consideration the interactions on PHY and MAC layers. The model, at the PHY layer level, is derived from the Zuniga and Krishnamachari mathematical framework for quantifying link unreliability. The MAC layer model is inspired from an enhanced Park et al. Markov chain. The joint model that combines both PHY and MAC models enables us to consider the causes behind packet losses either at PHY or MAC levels. Indeed, in the Park et al. model, collisions appear to be the only reason for losses, whereas, our model includes constraints posed by SNR (signal-to-noise ratio), modulation, encoding and asymmetry (heterogeneous hardware).

The remainder of this paper is as follows. In Section II, we present the related work which gives an overview of approaches that inspire our model. We focus on our contribution by giving details on the combined PHY and MAC layers models in Section III. In Section IV, we compare our proposition to the enhanced Park et al. approach and estimate nodes performances with different network densities. Finally, Section V concludes the paper and discusses some future research challenges.

## II. RELATED WORK

Many studies have aimed to understand and to evaluate standards and protocols. The works that tried to identify the properties of these networks mechanisms fall into two categories: i.e. simulations-based [2]–[6] relying on empiric observations, or analytical works [1], [7]–[9]. Most of analytical studies are based on the Markov model proposed by Bianchi [7] for the IEEE 802.11 standard. This model consists in a Markov chain that mimics the functionalities of the IEEE 802.11 standard while assuming a saturated traffic and ideal channel conditions. Zhai et al. [14] and Daneshgaran et al. [9] exploit the Bianchi model and extend it through more realistic assumptions. These approaches have inspired Griffith

and Souryal [15] to develop a model for the IEEE 802.11 MAC layer that adds a frame queue to each node. This contribution enables us to estimate the packet reception rate, the delay, the medium access control layer (MAC layer) service time and the throughput. Similar studies have been developed for the wireless sensor networks, and more especially the IEEE 802.15.4 standard. Hence, we note the models developed by Pollin et al. [16] and Park et al. [1]. The two approaches provide a generalized analysis that allows to measure reliability, delay and energy consumption. In each proposed model, the exponential backoff process is modeled by a Markov chain. Retry limits and acknowledgements in an unsaturated traffic scenario are also taken into consideration.

Park et al. propose a generalized analytical model of the slotted CSMA/CA mechanism with beacon enabled mode in IEEE 802.15.4. This model includes retry limits for each packet transmission. The scenario of a star network in which  $N$  nodes try to send data to a sink has been considered and defining the state of a single node through a Markov model has been proposed. Each state of the Markov chain is characterized by three stochastic processes: the backoff stage  $s(t)$ , the state of the backoff counter  $c(t)$  and the state of the retransmission counter  $r(t)$  at time  $t$ . The described modeling allows us to analyze of the link reliability, delay and energy consumption.

In another context, numerous works focus on the physical layer modeling. For instance, Zuniga and Krishnamachari [10], [11] have analyzed the major causes behind unreliability [10], [11] and the negative impact of asymmetry on link efficiency [11] in low power wireless links. Instead of the binary disc-shaped model these models reproduce the called *transitional region* [3]–[5] in order to model the transmission range. The packet reception rate and the upper-layer protocol reliability are highly instable when a neighbor is located in this region. To understand it, two models have been proposed: a channel model that is based on the log-normal path loss propagation model [17] and a radio reception model closely tied to the determination of packet reception ratio. Through these models, it is possible to derive the expected distribution and the variance of the packet reception ratio according to the distance.

### III. DEVELOPED IEEE 802.15.4 MODEL FOR SMART GRID

Our contribution joins the initiative of Smart Grid [15] to provide tools that evaluate wireless communications standards. The developed model that we propose analyzes an IEEE 802.15.4 PHY and MAC layer channel in which multiple non-saturated stations compete in communicating with a sink. The aim is to combine two relevant models: A PHY model that bypasses the disk shaped node range and takes into consideration the called transitional region and a MAC model that reproduces the CSMA/CA mechanism. The model described enables us to add the impact of PHY layer errors onto the MAC layer and to provide some improvements for the adopted MAC model, in order to obtain more precise output estimations. Our developed model is available at the SGIP NIST Smart Grid Collaboration website [15].

#### A. IEEE 802.15.4 PHY Model Description

To model the PHY layer, we have adopted the Zuniga and Krishnamachari approach [10], [11]. The main objective is to identify the causes of the transitional region and quantify their influence on performance without considering interferences (assumption of a light traffic or static interference). To do this, the expressions of the packet reception rate as function of distance are derived. These expressions take into account radio and channel parameters such as the path loss exponent (log-normal shadowing path loss model [17]), the channel shadowing variance, the modulation, the coding and hardware heterogeneity. They describe how the channel and radio influence transitional region growth. We use mathematical frameworks provided to compute packet delivery rate independently of interferences. For more details of the Zuniga and Krishnamachari models see [10], [11].

We believe that including the PHY model in the MAC model considered (the next subsection describes the MAC model) is an interesting challenge. Indeed, collisions are the major factor behind frame losses. Nonetheless, considering errors that can happen at the PHY layer includes constraints imposed by SNR (signal-to-noise ratio), modulation, encoding and asymmetry (heterogeneous hardware). Therefore, our contribution allows us to have a more realistic estimation by taking into account the causes of failures at both layers.

#### B. Operation details for the IEEE 802.15.4 MAC Model and the interactions with the PHY Model

The model of IEEE 802.15.4 MAC layer is inspired from Park et al. Markov chain [1]. It captures the state of the station backoff stage, the backoff counter and the retransmission counter. We insert into Park et al. model an M/M/1/K queuing model that endows a finite buffer to a station. On the one hand, the Markov model determines the steady state probability when a station senses the channel in order to transmit a frame and the probability that a frame experiences a failure (due to a collision or to PHY layer failure). On the other hand, the queuing model gives as output some measurements such as the throughput or the probability that the station is idle.

The Park et al. approach, inspired from [16], consists in a generalized analytical model of the slotted CSMA/CA mechanism of beacon enabled IEEE 802.15.4 with retry limits for each packet transmission (the complete description is provided in [1]). The model takes the scenario of  $N$  stations that try to communicate with a sink. Park et al. define the probabilities for the following events: a node attempts a first carrier sensing to transmit a frame, a node finds the channel busy during CCA1 or a node finds the channel busy during CCA2. They are denoted by the variables  $\tau$ ,  $\alpha$  and  $\beta$  respectively. These three probabilities are related by a system of three non-linear equations that arises from finding the steady state probabilities. Our model, described by the flowchart presented in Fig. 1 (the main PHY and MAC inputs are listed in Table I and Table II respectively), aims to solve the non-linear system that expresses these probabilities. In addition, it estimates  $p_0$ , the probability of going back to the idle state

by considering the offered load per node parameter  $\lambda$ . In this way, our contribution enables the MAC model to determine this probability, in opposition to [1] ( $p_0$  is taken as an input for the performances analysis).

We start from equations (16), (17) and (18) in [1] and make changes in some of these expressions to enhance the model. The equations (17) and (18) are expressed with probability  $\tau$  to mention that a node is transmitting. In our mind, this consideration is insufficient because a transmitting node must not be idle, that is why we substitute  $\tau$  by  $(1-p_0)\tau$ . Thereby,  $\tau$  is the probability that a node tries to transmit and  $1-p_0$  is the probability that a station has a frame to send. The system considered is given by equations (1), (2) and (3):

$$\tau = \left( \frac{1-x^{m+1}}{1-x} \right) \left( \frac{1-y^{n+1}}{1-y} \right) b_{0,0,0} \quad (1)$$

$$\alpha = \left( L + \frac{N(1-p_0)\tau(1-\tau(1-p_0))^{N-1}}{1-(1-\tau(1-p_0))^N} L_{ACK} \right) \quad (2)$$

$$\beta = \frac{1-(1-\tau(1-p_0))^{N-1}}{DV} + \frac{N(1-p_0)\tau(1-(1-p_0)\tau)^{N-1}}{DV} \quad (3)$$

Where  $DV = 2 - (1 - (1 - p_0)\tau)^N + N(1 - p_0)\tau(1 - (1 - p_0)\tau)^{N-1}$ ,  $x = \alpha + (1 - \alpha)\beta$  and  $y = P_{fail}(1 - x^{m+1})$ . The parameter  $P_{fail}$  represents the probability of a failed transmission attempt,  $m$  is the maximum number of backoffs the CSMA/CA algorithm will attempt before declaring a channel access failure,  $n$  is the maximum number of retries allowed after a transmission failure,  $L$  is the length of the data frame in slots (a slot has a length of 80 bits),  $L_{ACK}$  is the length of an acknowledgement in slots,  $N$  is the number of stations and  $b_{0,0,0}$  is the state where the state variables of the backoff stage counter, the backoff counter and the retransmission counter are equal to 0 (an approximation is proposed in [1]).

The mechanism that computes these probabilities (using the MATLAB *fsolve* function) allows us to determine the probability of failed transmission  $P_{fail}$ , given by:

$$P_{fail} = 1 - (1 - P_{col})(1 - P_e) \quad (4)$$

Where  $P_{col} = 1 - (1 - \tau(1 - p_0))^{N-1}$ .

In the above expressions,  $P_e$  is the probability of loss due to channel and radio constraints (computed by the PHY model) and  $P_{col}$  is the probability of a collision occurring (modified as done with (17) and (18) in [1]).

This mechanism is embedded in a loop that updates  $p_0$ . The developed model solves the system of non-linear equations to determine  $\tau$ ,  $\alpha$ ,  $\beta$  and therefore  $P_{fail}$ . Then,  $P_{fail}$ ,  $\alpha$  and  $\beta$  are used to estimate the mean MAC service time, or the mean time to process a frame, expressed also as Expected Time or  $ET$  (in [1], Section V.B details how to compute this time. We substitute, of course,  $P_{col}$  by  $P_{fail}$  to catch errors that can occur at PHY and MAC layers). So, a new value for  $p_0$  is

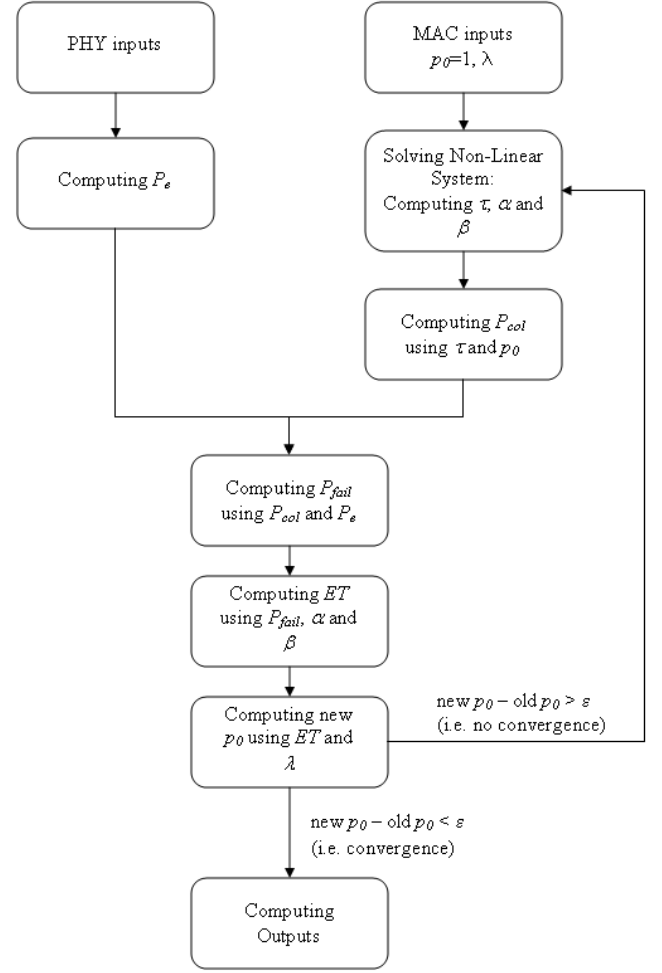


Fig. 1. IEEE 802.15.4 PHY and MAC model flowchart

generated and the updated  $p_0$  is used in the next iteration. It is possible to determine  $p_0$  since each device has a buffering capacity. Every node is modeled as an M/M/1/K queue and each queue receives frames following a Poisson arrival process  $\lambda$  frames/s. The queue utilization  $\rho$  is the product of the arrival rate  $\lambda$  and the inverse of the mean MAC service time  $ET$ . The steady state probability that there are  $i$  frames in the queue is:

$$p_i = \rho^i / \sum_{j=0}^K \rho^j \quad (5)$$

Hence, the value of  $p_0$  is given by:

$$p_0 = \left[ \sum_{j=0}^K \rho^j \right]^{-1} \quad (6)$$

The process continues until the value of  $p_0$  converges to a stable value. Once  $p_0$  converges, all outputs concerning queuing analysis can be computed for each value of  $\lambda$  (the per-node load offered). Four outputs are considered in this

study: the average waiting time to receive a frame (Eq. (7)), the failure probability (probability of packet loss due to collisions or link constraints)(Eq. (4)), the reliability of a node (the probability of a good frame reception)(Eq. (8)) and the average throughput per node(Eq. (9)).

$$D = \frac{L}{\lambda(1 - p_k)} \quad (7)$$

$$R = (1 - p_k)(1 - P_{cf})(1 - P_{cr}) \quad (8)$$

$$S_{avg} = \lambda R L_p \quad (9)$$

Where  $p_k$  is the probability of having full buffer,  $P_{cf}$  is the probability that the frame is discarded due to channel access failure (Eq. (19) in [1]),  $P_{cr}$  is the probability that the packet is discarded due to retry limits (Eq. (20) in [1]),  $L$  is the payload size and  $L_p$  is the application data size.

Therefore, this contribution enables us to enhance Park and al. model at two levels:

- Providing a more precise computation of failure probability by considering possible errors at PHY and MAC layers (link unreliability and collisions).
- Enhancing the MAC model of Park et al. by estimating the probability  $p_0$  for the resolution of non-linear equations (this probability is an input in Park et al. model), modifying some expressions to more efficient estimations and determining outputs relative to a precise scenario (number of nodes and per-node load offered).

#### IV. SIMULATION AND RESULTS

We propose two scenarios for the simulations. Firstly, we compare the performances of a node obtained in two different ways. On one hand, we use the Park et al. Markov chain (MAC layer) and on the other hand we test our model. Secondly, we expose the same performances, using our developed model, for different densities. Table I presents the main inputs at the MAC layer and Table II enumerates the main ones at the PHY layer. All the simulations test different values for the offered per-station load, measured in units of frame/s. We choose to start from 0.5 frame/s and increase the offered load to 25 frames/s with a step of 0.5 frame/s (or from 400 bits/s to 20000 bits/s). We select four outputs to illustrate node performances: the average waiting time for a frame reception, the failure probability (probability of frame loss due to collisions or link constraints), the reliability of a node (the probability of a good frame reception) and the throughput.

##### A. Comparison between combined PHY and MAC layers and simple MAC layer models

As described in Section III, when we include the constraints at the physical layer, delivery failures happen more often. There are many reasons for this: weak SNR and modulation and/or encoding errors. We run simulation for a star network with 10 nodes. The results confirm a notable degradation of node performances. In Fig. 2(a), the average waiting time is for the the combination of the PHY and MAC models. Inserting link constraints increases the number of retransmissions. Thus,

TABLE I  
MAIN PARAMETERS USED IN MAC LAYER

Parameter	Value	Parameter	Value
Number of Nodes	5, 10, 50	Queue Size	51 Frames
Smallest Backoff Win	8	Data Rate	19.2 kbit/s
Max Frame Retries	3	ACK Size	88 bits
Max CSMA Backoff	4	Shadowing STD	4
Max Backoff Exponent	5	IFS	640 $\mu$ s
Min Backoff Exponent	3	Max TX-RX Time	192 $\mu$ s
MAC Frame Payload	800 bits	MAC Overhead	48 bits

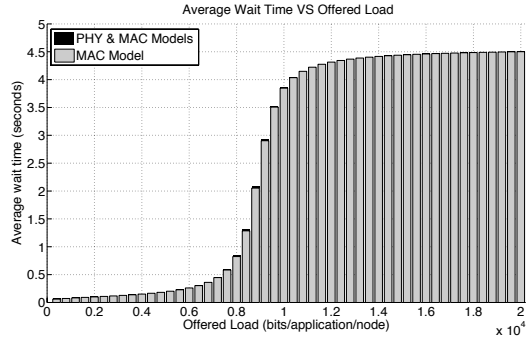
TABLE II  
MAIN PARAMETERS USED IN PHY LAYER

Parameter	Value	Parameter	Value
Noise Figure	23dB	Bandwidth	30kHz
Pathloss exp	4	STD Tx power	5dBm
Noise	15dB	Preamb. Length	40 bits
Max Tx range	20 m	Min Tx Range	1 m

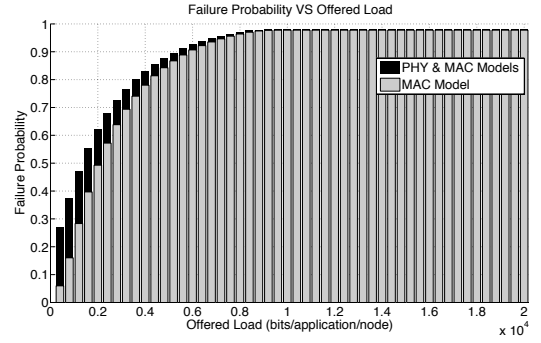
the delay increases. The delay difference between the two approaches reaches 40 ms at offered load equal to 11 frames/s. Fig. 2(b) compares the evolution of failure probability for the two approaches. With light offered loads, the impact of the PHY model is conspicuous, especially since the number of collisions is likely to be low. The collisions are more frequent with heavier loads and the probability of occurrences grows quickly, generating network saturation. Meanwhile, the probability of losses due to link conditions remains constant (this probability is determined independently of interferences and computed through an integration over the distance covered by the maximum range and over asymmetry variations). So, the difference between the two approaches is less significant. The same interpretation can be used for reliability evolution, presented in Fig. 2(c). Reliability also undergoes the frame discards due to the reaching of maximum frame retries or maximum CSMA backoffs. The rejected frames due to full node queue represent also a possible interpretation with high offered loads. The throughput evolution, presented in Fig. 2(d), also undergoes the constraints of the PHY layer, and is logically less significant since it follows the same evolution of reliability (throughput is the product of reliability, offered load and data frame size).

##### B. Evolution of node performance with growing densities

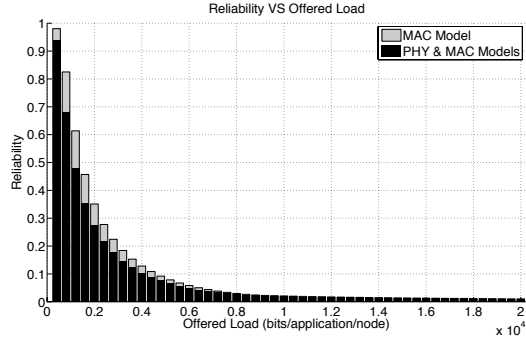
We use our model to compare node performances with three densities. We propose a network with 5 nodes, another with 10 nodes and a third with 50 nodes. We take into account the same outputs cited in the previous section. The major observation is that the IEEE 802.15.4 networks do not support heavy traffic. The denser the network is, the poorer are the performances are. We note an increasing delay for denser networks, as observed in Fig. 3(a). As the number of nodes increases, and with growing offered loads, collisions are more frequent and so the retransmissions are more recurrent. The switching phase to saturated network shows more significant differences



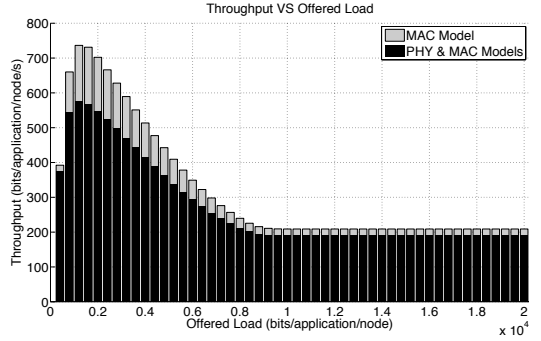
(a) Average wait time versus load offered



(b) Failure probability versus load offered

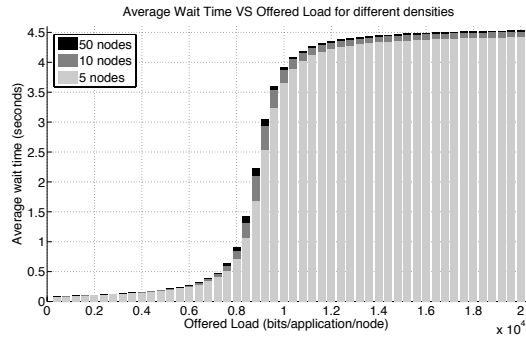


(c) Reliability versus load offered

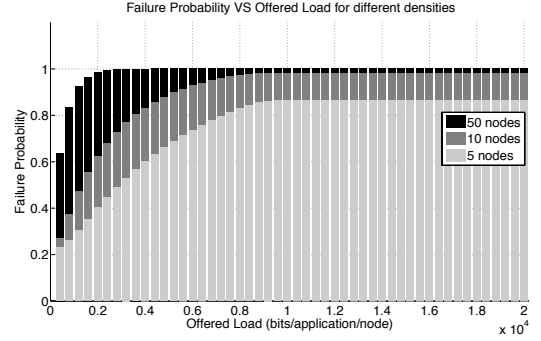


(d) Throughput versus load offered

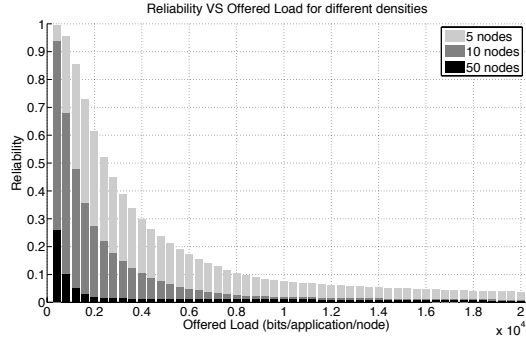
Fig. 2. Comparison between IEEE 802.15.4 PHY & MAC Model and IEEE 802.15.4 MAC Model



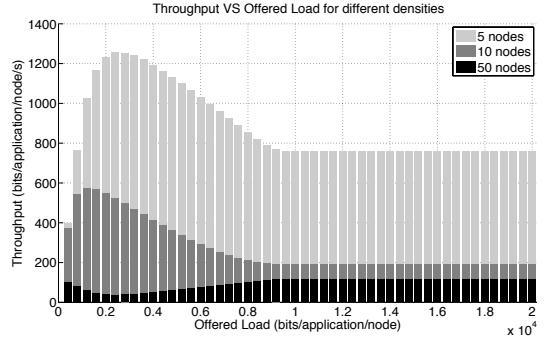
(a) Average wait time versus load offered



(b) Failure probability versus load offered



(c) Reliability versus load offered



(d) Throughput versus load offered

Fig. 3. Performances evolutions for different densities using IEEE 802.15.4 PHY & MAC Model

between the three network scenarios. Each node queue begin to experience congestion problems; with more retransmission requirements, the queues are busier and the delays are longer. At saturation, the frame losses are widespread (collisions, link constraints, frames discarded due to retry limits, etc.) for the three scenarios, but the number of nodes still has an impact because it has a negative influence on performances and channel availability (more collisions, more retransmissions, channel congestion, ...). The same reasoning explains a higher failure probability, as presented in Fig. 3(b) and a lower reliability as outlined in Fig. 3(c) for denser networks and with increasing offered load. The evolution of throughput, shown in Fig. 3(d), also matches with the interpretations cited above.

## V. CONCLUSION

We have presented, in this paper, a model that mimics the IEEE 802.15.4 functionalities at the PHY and the MAC layers. We aim to combine two relevant propositions. On the one hand, we model constraints that affect link quality using the Zuniga and Krishnamachari mathematical framework: distance, output power, noise, asymmetry and errors related to encoding and modulation. The PHY model bypasses the disk-shaped node range and expresses more precisely the degree of link unreliability. The output of this model represents an important outcome for estimating more faithfully the probability of transmitting frame failure. On the other hand, we enhance the Park et al. IEEE 802.15.4 MAC layer model to extract the delay and the reliability. Our contribution seeks to improve the Park et al. approach in determining inherent probabilities (frame transmission, free channel in CCA1/CCA2, failure,...) and combining it with the PHY model to better estimate wireless network parameters. The methodology adopted relies on a Markov chain that follows the flowchart described in Fig.1 and on an M/M/1/K queue that we includes with the Park et al. approach. The joint model is available at the SGIP NIST Smart Grid Collaboration website [15] for use.

The simulations show that more precise estimations are provided by our model versus that by the Park et al. MAC model. The comparison between the two considerations highlights a notable performance deterioration using the combined model. This observation is quite logical since this combination joins PHY constraints to collisions. Thus, our contribution improves the Park et al. approach by bypassing the assumption that failures are restricted to collisions. The amelioration of the Park et al. approach is not limited to the above description. We try also to enhance the estimation of inherent probabilities by adjusting some expressions (as for  $\alpha$ ,  $\beta$  and  $P_{fail}$ ) and modifying the resolution method to gather new parameters (such as  $p_0$ , the probability that a node returns to the idle state, which is considered as an input in Park et al. work).

Our contribution proposes to mimic the IEEE 802.15.4 PHY and MAC layers mechanisms. Nonetheless, it is extensible for reproducing more precise wireless networks standards related to IEEE 802.15.4. It is also adjustable to other standards. Indeed, the considered PHY layer model is quite relevant but assumes that interferences are weak and/or stable. Moreover,

the probability of an error at the PHY layer is averaged (through integration over maximum range and maximum asymmetry variation). Hence, as future work, we will seek to extend our model in order to consider distance between nodes and thereby topologies. Also, it will be challenging to plan a model that deals with node mobility to appreciate its impact on performances. From there, our model can be used as a tool to verify metrics efficiency in mobile environments.

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